

**Collision Rates in the Present-Day Kuiper Belt and Centaur Regions:  
Applications to Surface Activation and Modification  
On Comets, Kuiper Belt Objects, Centaurs, and Pluto-Charon**

Daniel D. Durda and S. Alan Stern  
Southwest Research Institute  
Space Studies Department  
1050 Walnut Street, Suite 426  
Boulder, CO 80302  
durda@boulder.swri.edu

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**Address editorial correspondence to:**

Daniel D. Durda  
Southwest Research Institute  
1050 Walnut Street  
Suite 426  
Boulder, CO 80302  
  
Tel: (303) 546-9670  
Fax: (303) 546-9687  
durda@boulder.swri.edu

## ABSTRACT

We present results from our model of collision rates in the present-day Edgeworth-Kuiper Belt and Centaur region. We have updated previous results to allow for new estimates of the total disk population, in order to examine surface activation and modification time scales due to cratering impacts. We extend previous results showing that the surfaces of Edgeworth-Kuiper Belt objects are not primordial and have been moderately to heavily reworked by collisions. Objects smaller than about  $r = 2.5$  km have collisional disruption lifetimes less than 3.5 Gyr in the present-day collisional environment and have probably been heavily damaged in their interiors by large collisions. In the 30–50 AU region, impacts of 1 km radius comets onto individual 100 km radius objects occur on  $7 \times 10^7$ – $4 \times 10^8$  yr time scales, cratering the surfaces of the larger objects with  $\sim 8$ –54 craters 6 km in diameter over a 3.5 Gyr period. Collision time scales for impacts of 4 meter radius projectiles onto 1 km radius comets range from  $3$ – $5 \times 10^7$  yr. The cumulative fraction of the surface area of 1 and 100 km radius objects cratered by projectiles with radii larger than 4 m ranges from a few to a few tens percent over 3.5 Gyr. The flux of Edgeworth-Kuiper Belt projectiles onto Pluto and Charon is also calculated and is found to be  $\sim 3$ –5 times that of previous estimates. Our impact model is also applied to Centaur objects in the 5–30 AU region. We find that during their dynamical lifetimes within the Centaur region, objects undergo very little collisional evolution. Therefore, the collisional/cratering histories of Centaurs are dominated by the time spent in the Edgeworth-Kuiper Belt rather than the time spent on planet-crossing orbits. Further, we find that the predominant surface activity of Centaur objects like Chiron is most likely not impact-induced.

**Keywords:** Centaurs, Chiron, Comets, Kuiper Belt Objects, Pluto

## 1. INTRODUCTION

Collisions are the dominant evolutionary process acting on most small bodies in the solar system. In the main asteroid belt, for instance, cratering collisions have greatly modified the surfaces of individual asteroids by leaving large impact scars (e.g., Greenberg *et al.* 1994, 1996; Veverka *et al.* 1997) and redistributing regolith across their surfaces (Geissler *et al.* 1996), and catastrophic collisions over the aeons have left their mark on the entire population size distribution (Davis *et al.* 1979, 1989; Durda *et al.* 1998).

The Edgeworth-Kuiper Belt (EKB) population represents another major population of small bodies whose evolution is largely shaped by collisions (Stern 1995). Stern (1996) and Davis and Farinella (1997) have further explored the rate of collisions between comets in the region beyond 30 AU, and found that collisional evolution is a highly important process in the EKB. Collisional evolution in the EKB has recently been reviewed by Farinella *et al.* (2000).

Although intrinsic collision rates (number of collisions per kilometer<sup>2</sup> per year) are lower by a factor of  $\sim 1000$  in the EKB compared to the main asteroid belt, the population of objects there is  $\sim 1000$  times as great. As a result of these competing factors, the overall level of collisional processing of individual objects is of similar scale to that in the main belt.

Here we seek to investigate the implications of the EKB collision rates for surface modification. In particular, we wish to estimate quantities such as the surface cratering fractions, and the expected largest crater sizes. In addition to a direct relevance for understanding comets and other objects in the EKB, we also seek to gain insights into what the Pluto-Kuiper Express spacecraft (Terrile *et al.* 1997) may observe when it images the surfaces of Pluto, Charon, and other EKB objects. Similarly, we seek to assess whether Centaur objects on transient orbits in the giant planet region undergo further significant collisional processing.

In what follows we first revisit previous collision rate calculations (Stern 1995, 1996) in light of both new observational data, and higher fidelity modeling. Once improved collision rates are obtained, we go on to evaluate their effect on the surfaces of objects in, and derived from, the Edgeworth-Kuiper Belt.

## 2. THE COLLISION RATE MODEL

Stern (1995) examined collision rates in the present-day Edgeworth-Kuiper Belt beyond 30 AU, as a function of the disk's radial and population size structure. The numerical model for calculating collision rates is described in detail in that paper, so only a brief recapitulation will be presented in this section; in the next section we will describe changes and improvements that have been made to the model to produce the results presented later in this paper.

The 1995 model is a static, multi-zone, multi-size-bin, particle-in-a-box collision rate model that calculates instantaneous collision rates. The colliding population is defined in

terms of a total disk mass and a single-valued power-law size distribution of objects in the disk, normalized by the total number of  $\sim 100$  km diameter and larger objects in the 30–50 AU zone. This size distribution is treated as a series of monotonically increasing radius  $r$  bins, with the objects in each successive bin 1.6 times larger in size (and 4 times more massive) than those in the preceding bin.<sup>[1]</sup> The model also specifies the radial distribution of heliocentric surface mass density  $\Sigma(r)$  so that:

$$\Sigma(r) = \Sigma_o r^\beta, \quad (1)$$

where  $\Sigma_o$  is a normalization constant which in effect specifies a total EKB mass in the 30–50 AU zone. The power-law exponent  $\beta$  determines the heliocentric radial distribution of mass in the disk, with the two cases we consider defining a realistic range of parameter space:  $\beta = -1$  corresponds to a constant mass per heliocentric radial bin, while  $\beta = -2$  (more realistic, and our preferred case), corresponds to a declining mass per radial bin. A disk-wide average eccentricity,  $\langle e \rangle$ , is adopted for each model run; an equilibrium condition where the disk wedge angle  $\langle i \rangle = \frac{1}{2} \langle e \rangle$  is assumed (see, e.g., Lissauer and Stewart 1993).

Once the global properties of the disk are specified, the disk is binned into a series of radially concentric tori 1 AU in width, and the collision rates for objects at each semimajor axis are then calculated in a particle-in-a-box formalism. In this approach, the instantaneous collision rate  $\bar{c}$  (collisions/unit time) of target bodies with semimajor axis  $a$ , eccentricity  $e$ , and radius  $r_k$  being struck by impactors of radius  $r_l$  is

$$\bar{c}(r_k, r_l, a, e, i, R) = \sum_{R=a(1-\langle e \rangle)}^{a(1+\langle e \rangle)} \sqrt{\frac{GM_\odot}{4\pi^2 a^3}} T(a, \langle e \rangle, R) n(r_l, R) v_{kl}(a, \langle e \rangle, \langle i \rangle, R) \sigma_g(r_k, r_l, v_{kl}, v_{esc[k+l]}), \quad (2)$$

where  $T(a, \langle e \rangle, R)$  represents the time the target body spends at each distance  $R$  during its orbit.  $T(a, \langle e \rangle, R)$  is computed by solving the Kepler time-of-flight equation explicitly for every  $(a, \langle e \rangle)$  pair in the model’s parameter space. The number density of impactors  $n(r_l, R)$  in the torus centered at distance  $R$  is computed from the mass of the disk, the disk’s wedge angle  $\langle i \rangle$ , its population size distribution, and its heliocentric surface mass density structure (Eq. 1). Here  $v_{kl}$  is the local average crossing speed of the impactor population against the targets,  $v_{esc}$  is the escape speed of the combined target-projectile pair, and  $\sigma_g$  is the gravitational-focusing corrected collision cross section.

### 3. MODEL IMPROVEMENTS AND INPUT PARAMETER UPDATES

We have made two noteworthy improvements to the model outlined above. These are:

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<sup>[1]</sup> The radius of the smallest bin was 3.94 m; successive bin radii were 6.25 m, 9.92 m, etc.

- A more exact treatment of relative impact speeds. In the earlier model, relative impact speeds were calculated by a “particle-in-a-box” approximation of the orbital motion of the target:  $v = (\langle e \rangle^2 + \langle i \rangle^2)^{1/2} v_k$ , where  $v_k$  is the average Keplerian orbital speed of the target. We now include in the collision rate calculations the difference between the collision frequency of bodies in mutual Keplerian orbits and that based on “particle-in-a-box” collisions, so that  $v = (\frac{5}{4}\langle e \rangle^2 + \langle i \rangle^2)^{1/2} v_k$ , as well as the effect of a Gaussian speed distribution (cf., Wetherill and Stewart 1993, Appendix A).
- Setting realistic limits on gravitational focusing. Previously, the effects of gravitational focusing were unconstrained, allowing the collision cross section  $\sigma_g$  to grow unrealistically large for the most massive targets and for very low  $\langle e \rangle$ . In the present model we now include limits on the gravitational focusing factor due to Keplerian shear, 3-body effects, and velocity dispersion (cf., Ward 1996, Eqs. 9 and 11).

These improvements are numerical refinements affecting the final results at only about the 10% level as compared with our previous calculations; nonetheless, they are worth documenting and make the final results more robust. Of greater importance, we have updated the input parameters necessary to compute collision rates in the EKB, based on observational advances that have occurred since 1995. In particular, these are:

- Jewitt *et al.* (1998) and Gladman *et al.* (1998) have each provided convincing evidence that between 30–50 AU there exist at least 70,000 objects with  $r > 50$  km, and perhaps twice that many. This is between 2 and almost 5 times the population estimates for such bodies available in 1995. We therefore conduct new model runs with normalizations of both  $7 \times 10^4$  and  $1.4 \times 10^5$  objects with  $r > 50$  km.
- Further, the population size distribution is now represented by a more sophisticated, two-component power law of the form  $N(d_i) \propto d_i^b dd_i$ , where  $b = -3$  for  $d_i < d_0$  and  $b = -4.5$  for  $d_i > d_0$ , with  $d_0 = 10$  km (Weissman and Levison 1997; hereafter WL97).<sup>[2]</sup>

For reference, a WL97 size distribution, coupled with an estimated population of 70,000 objects with  $r > 50$  km, yields  $\sim 4564$  objects in our model’s  $r = 102.4$  km size bin and  $\sim 1.2 \times 10^9$  objects in the  $r = 1$  km size bin. For a population of 140,000 objects larger than  $r = 50$  km, the number of objects in all size bins doubles accordingly. We continue to model the spatial distribution of objects in the 30–50 AU region as a disk, with our preferred surface mass density index  $\beta = -2$ , as described above.

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<sup>[2]</sup> At large sizes the WL97 size distribution is consistent with the latest estimates by other researchers (Gladman *et al.* 1999, for instance). For smaller, comet-size objects, simple, single power-law extrapolations from larger sizes appear to over-estimate the number of small EKB objects needed to supply the short-period comet flux (Duncan *et al.* 1995), hence the broken power law of WL97.

We have compared our modeled collision rates with those computed from the observed distribution of EKO orbits (Bottke 1999; personal communication) and find very good agreement between the two independent methods. Our modeled collision rates, discussed in the following sections, are within a factor of  $\sim 2\text{--}4$  of those calculated based on an Öpik-style collision rate model (Bottke *et al.* 1994) applied to the observed EKO orbit distribution. Considering the fact that we have not made any attempt to bias-correct the observed orbit distribution for this comparison, and the fact that our disk model has an inclination distribution that is somewhat ‘colder’ than the observed EKO population<sup>[3]</sup>, we consider the agreement between the two calculations quite good.<sup>[4]</sup>

## 4. NEW ESTIMATES OF COLLISION RATES IN THE KUIPER BELT

### a. Collision Outcomes

We now present results of collision rate calculations for the 30–50 AU region obtained with our improved collision model and updated input parameters.

First, however, it is important to remember that given the dynamical conditions of the present EKB, mutual collisions between Edgeworth-Kuiper Belt objects (EKOs) are generally erosive. That is, above some critical eccentricity,  $e^*$ , impacts occur at relative speeds high enough that most ejecta escapes the target bodies. Figure 1 shows the critical eccentricity boundary between erosional (i.e., net mass loss) and accretional (i.e., net mass gain) regimes for mutual collisions between EKOs (see Stern 1996). Our contribution here, in Figure 1, is the addition of some 128 multi-opposition EKOs for which fairly reliable orbits have been determined, so that this large population of objects with moderately-well established orbits can be evaluated relative to the critical eccentricity boundary curves.

Notice that the critical eccentricity for mutually colliding objects in the EKB increases slightly with increasing heliocentric distance due to the direct linear dependence of the typical approach speed upon the local Keplerian orbital speed. Farther from the Sun, higher  $\langle e \rangle$ ’s are required to generate impact energies sufficient to guarantee erosive collisions. Thus, if  $\langle e \rangle$  does not increase with heliocentric distance, collisions will tend to be less erosional in nature as we move outward through the EKB. For  $\langle e \rangle$  greater than the critical eccentricity,  $e^*$ , impacts eject more target mass than is retained, and the target is either disrupted in response to a catastrophic collision, or eroded in the case of a cratering collision.

The plotted data points for 128 multi-opposition EKOs show that most large EKOs, like the main-belt asteroids, are currently undergoing predominantly erosive collisions, even

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<sup>[3]</sup> Relative to observed EKO eccentricities, observed inclinations are higher than the  $\langle i \rangle = \frac{1}{2}\langle e \rangle$  equilibrium values assumed in our model.

<sup>[4]</sup> Nevertheless, we remind the reader about the large model uncertainties attributable to using simple power laws for both the orbital and the population size distributions.

under the most pessimistic assumption, i.e., that of strong surface mechanical properties. As to classical, km-scale comets (i.e., those objects which leave the EKB to appear as the Jupiter Family comets),  $e^*$  values are so low as to guarantee that these bodies have resided in a heavily erosional collisional environment.

## b. Collision Rates and Fluxes

Figure 2 shows the typical number of collisions which occur onto 100 km- and 1 km-scale radius EKO as a function of projectile radius, at both 35 and 45 AU.

The calculations shown here assume the “nominal” estimated population<sup>[5]</sup> of such objects in the 30–50 AU zone today, i.e.,  $N(r > 50 \text{ km}) = 7 \times 10^4$ . Since the collision rate model used here is static (i.e., it calculates collision rates for the present disk and does not account for a decrease in the population size with time as bodies are collisionally destroyed), we calculate the total flux of impactors on a target only over the last 3.5 Gyr, the approximate time since which the disk is expected to have reached roughly its present mass and dynamical state (e.g., Weissman and Levison 1997).<sup>[6]</sup> Our interest here is in present-day collisional rates and effects. This is primarily because the small bodies in the EKB are young compared to 3.5 Gyr (Stern 1995; Davis and Farinella 1997), and bodies of all sizes underwent far more significant collisional processing in the more massive, primordial Kuiper disk (Stern and Colwell 1997).

Figure 2 shows that a typical, 100 km-scale radius EKO will have undergone  $\sim 8$ –54 cratering impacts with 1 km radius “comets” over the last 3.5 Gyr, depending on heliocentric distance and  $\langle e \rangle$ . At 35 AU the collision time scales for a typical EKO are  $6.5 \times 10^7$  and  $1.5 \times 10^8$  yr for  $\langle e \rangle = 0.0256$  and  $0.2048$ , respectively. The same collision time scales are  $1.4 \times 10^8$  and  $4.1 \times 10^8$  yr at 45 AU for the same  $\langle e \rangle$ ’s. These values of  $\langle e \rangle$  cover the range of observed  $e$  for most EKO. For large EKO, collision time scales are shorter for smaller  $\langle e \rangle$ ’s due to increased gravitational focusing effects at smaller encounter speeds. Given our estimated population of 100 km radius EKO in the EKB (4564 objects in the size bin with radii between 81–129 km), there should be one such EKO-comet collision somewhere in the 30–50 AU region every  $\sim 1.4$ – $9.0 \times 10^4$  yr. Smaller projectiles hit more frequently, with impact time scales for 4 m radius projectiles onto any single 100 km-scale radius target of  $\sim 1000$ –6000 yrs; across the entire EKB, such cratering impacts occur every  $\sim 80$ –510 days.

Figure 2 also shows the number of collisions onto a 1 km radius comet. Over 3.5 Gyr<sup>[7]</sup> a 1 km radius comet between 35 and 45 AU will experience  $\sim 90$ –300 cratering collisions with

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<sup>[5]</sup> In what follows we will report collision time scales and impact fluxes for the “nominal” population only. For a larger population with  $N(r > 50 \text{ km}) = 1.4 \times 10^5$ , reported collision time scales for individual objects will be reduced by a factor of 2 and impact fluxes will be increased by a factor of 2.

<sup>[6]</sup> For this reason, we denote any object or surface unit on an object of this age as “primordial” if it is this age or older.

<sup>[7]</sup> In the next subsection we show that catastrophic disruption lifetimes for 1 km radius



projectiles larger than  $r = 4$  m. Collision time scales for impacts of 4 m radius projectiles onto 1 km radius targets range from  $2.5\text{--}4.7 \times 10^7$  yr. Over the entire population of  $\sim 2 \times 10^9$  comets in the disk, there should be one such collision every several days. These numbers assume, of course, that the WL97 size distribution is valid to sizes as small as 4 m. The actual size distribution of small objects in the EKB is highly uncertain, and the cratering records of the Galilean satellites may even hint at a lack of cometary objects smaller than  $\sim 100$  m (Chapman 1997; Chapman *et al.* 1998).

### c. Catastrophic Disruption Lifetimes and Deep Interior Modification

What about larger collisions and the likelihood that a 100 km radius EKO would be catastrophically disrupted over 3.5 Gyr? The impact scaling literature has been dominated by consideration of collisions between asteroids, so the impact specific energies and scaling laws used here are most appropriate for silicate targets. However, Ryan *et al.* (1999) have conducted laboratory impact studies in which porous ice targets were impacted by fractured ice projectiles to simulate collisions between EKOs, and found that impact specific energies and fragmentation modes are similar to those for silicate targets. Smooth particle hydrodynamics calculations by Benz and Asphaug (1999) indicate that impact specific energies for basalt targets are only  $\sim 2\text{--}4$  times greater than those for icy objects under the same impact conditions. Estimates of the impact specific energy,  $Q_D^*$ , required to catastrophically disrupt and disperse a 100 km radius object range from  $\sim 1\text{--}4 \times 10^5$  J kg $^{-1}$  (Davis *et al.* 1989; Love and Ahrens 1996; Melosh and Ryan 1997; Durda *et al.* 1998).

With  $\langle e \rangle = 0.2048$ , effective relative impact speeds between 100 km radius EKOs and other objects in the 30–50 AU region range from  $\sim 1.1\text{--}1.4$  km s $^{-1}$ . The relative impact speed is  $v_i = (U^2 + v_{\text{esc}}^2)^{1/2}$ , where  $U$  is the hyperbolic encounter speed (dependent upon heliocentric distance and  $\langle e \rangle^{[8]}$ ) and  $v_{\text{esc}}$  is the escape speed of the combined target-projectile pair. At these speeds, the smallest object capable of delivering the required specific energy for disruption to the target is about  $r = 53\text{--}84$  km in size. The time scale for such a collision is presently  $3\text{--}8 \times 10^{12}$  yr (using a model bin radius of 64.5 km). Still-larger EKOs would have longer disruption time scales.

Our results show clearly that the vast majority of the largest EKOs are not likely to have been involved in disruptive collisions over the last 3.5 Gyr. This is in agreement with collisional models of EKB evolution by Davis and Farinella (1997), showing that the population at diameters larger than about 100 km is essentially unchanged over solar system history.

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comets in the EKB range from  $\sim 1\text{--}10$  Gyr. We calculate impact fluxes here over 3.5 Gyr in order to directly compare with results for larger objects; for shorter- or longer-lived comets, fluxes will be proportionately smaller or larger, respectively.

<sup>[8]</sup> The encounter speed is also dependent upon  $\langle i \rangle$ , but recall that we have assumed an equilibrium condition where  $\langle i \rangle = \frac{1}{2} \langle e \rangle$ .

Figure 3 shows the catastrophic disruption lifetimes for a range of EKO sizes at 35 and 45 AU with  $\langle e \rangle = 0.2048$ . Shattering time scales for 100 km radius objects are shorter,  $\sim 3.9$ – $10.5$  Gyr, since projectiles as small as  $r \approx 5$  km may fragment the target without dispersing the resulting debris, resulting in gravitationally re-accumulated rubble-pile EKOs.

What is the largest object size-class in which the majority of objects can be expected to have been involved in disruptive collisions in the EKB in the last 3.5 Gyr? Using our highest modeled  $\langle e \rangle$  of 0.2048 and the lowest estimated  $Q_D^*$  for objects of various sizes, and searching through the many combinations of our calculated target-projectile collision time scales, we find that objects smaller than  $r \approx 2.5$  km presently have catastrophic disruption time scales at 35 AU less than 3.5 Gyr. At 45 AU the disruption time scale increases by a factor of  $\sim 2.5$ – $3$ , so that smaller objects with radii less than about 1.6 km have lifetimes of 3.5 Gyr. At lower  $\langle e \rangle$  and assuming values of  $Q_D^*$  nearer the mid-range of published scaling laws, objects become harder to destroy, so that  $r \approx 2.5$  km should be considered an upper limit to the size object that can have a collisional disruption time scale less than 3.5 Gyr anywhere in the EKB.

From the collision rates yielded by our model, we can also calculate the collisional disruption lifetime in the EKB for a typical comet nucleus with radius  $r = 1$  km. We estimate the impact specific energy for disrupting such an object to be  $\sim 10$ – $200$  J kg $^{-1}$  (Durda *et al.* 1998; Melosh and Ryan 1997). Using these values for  $Q_D^*$ , and assuming disk-wide  $\langle e \rangle$  of 0.0256–0.2048, we find that at 35 AU a  $r = 1$  km comet can be destroyed by  $r \approx 0.02$ – $0.25$  km projectiles. The corresponding disruption lifetime ranges from  $\sim 9.6 \times 10^8$ – $10^{10}$  yr. At 45 AU the lifetime is  $\sim 2.6 \times 10^9$ – $10^{11}$  yr. Eccentricities for most observed EKOs tend to be near the higher of the values assumed here, so that disruption time scales for comets are likely near the lower values reported. Across the 30–50 AU region, we find collision lifetimes for  $r = 1$  km comets are then likely of order 1–10 Gyr, assuming mid-range values of  $Q_D^*$ .

## 5. SURFACE MODIFICATION IN THE EKB

### a. Cratering Fraction

The results of collision rate calculations presented in the previous section demonstrate that EKOs of all sizes have suffered a significant number of collisions. These collisions can be expected to have significantly affected the surfaces of both large and small objects, covering their surfaces with craters of various sizes, overturning and reworking underlying, more primordial surfaces, removing surface materials through impact sublimation, and possibly exposing deeper and more volatile icy species and thus possibly serving as a mechanism to activate distant, inactive objects.

Using the encounter speeds and impactor fluxes calculated in the previous section, we can estimate the sizes and spatial coverage of impact craters on typical EKOs. Holsapple (1993) gives an expression for the diameter of an idealized, hemispherical crater, as:

$$D = 1.26d(A\rho_{\text{impactor}}/\rho_{\text{target}})^{1/3}(1.61gd/v_i^2)^{-\alpha/3}, \quad (3)$$

where  $d$  is the impactor diameter,  $\rho$  is the density,  $g$  is the surface gravity of the target,  $v_i$  is the encounter speed, and  $A$  and  $\alpha$  are constants dependent upon the mechanical properties of the target material. Holsapple (1993) uses values of  $A$  and  $\alpha$  of 0.2 and 0.65, respectively, for water ice. For a 100 km-scale radius EKO with an assumed density of  $\rho = 1.5 \text{ g cm}^{-3}$ ,  $g \approx 4.3 \text{ cm sec}^{-2}$ . The relative encounter speed,  $v_i$ , as defined in the previous section, includes the escape speed of the combined target-projectile pair.

Figure 4 shows the fraction of a  $r = 102 \text{ km}$  target’s surface area covered by craters produced by projectiles of various sizes, over a 3.5 Gyr period. We find that the cumulative fraction of the surface cratered by all  $r > 4 \text{ m}$  projectiles ranges from  $\sim 7\text{--}32\%$ , for targets from 35–45 AU and for  $\langle e \rangle = 0.0256\text{--}0.2048$ . This is a conservative estimate that does not include the additional surface area covered by crater flanks and ejecta blankets, which would cover  $\sim 4$  times more area. Significant additional area will also be covered by craters produced by projectiles smaller than  $r = 4 \text{ m}$ , our lower size limit in these calculations. Overall, perhaps a third of the entire surface of a typical 100 km-scale EKO will have been re-worked by impact cratering over the past 3.5 Gyr.

Collision rates calculated in the previous section showed that comet-sized objects ( $r \approx 1 \text{ km}$ ) will also be significantly cratered during their lifetimes, typically enduring  $\sim 90\text{--}300$  impacts by objects larger than  $r = 4 \text{ m}$ . Figure 4 shows that a typical comet with  $r = 1 \text{ km}$  will have  $\sim 20\text{--}224\%$  of its surface cratered by impacts with  $r > 4 \text{ m}$  projectiles over 3.5 Gyr. Davis and Farinella (1997) concluded that most comet-size objects are collisional fragments of larger parent objects. Our results suggest that even the small fraction of objects surviving, “original” accretion products objects (i.e., those that are  $> 3.5 \text{ Gyr}$  old) will have undergone substantial collisional processing in the form of cratering and sub-catastrophic impacts.

This result extends the notion that the surfaces of EKOs are not primordial and have been moderately to heavily reworked during their history in the EKB (Stern 1995; Luu and Jewitt 1996; Davis and Farinella 1997; Farinella *et al.* 2000). The numerous smaller impactors, responsible for most of the spatial coverage, will have comminuted and gardened the surfaces of EKOs, producing a regolith of shattered, icy debris. As we will see below, EKO surfaces are expected to display both fresh and primordial (i.e.,  $> 3.5 \text{ Gyr}$  old) units.

Larger impactors will have penetrated deeper into the target’s surface, excavating material that is less impact-processed from below. The most recent, large impacts may have associated bright ejecta blankets and ray systems. Brown *et al.* (1999) report evidence that the intensity of water bands in the spectrum of 1996 TO<sub>66</sub> varies with rotational phase, which suggests a “patchy” surface. Fig. 2 shows that the largest impactors likely to have struck 100 km radius EKOs over the last 3.5 Gyr have  $r \approx 5 \text{ km}$ , resulting in craters  $\sim 26 \text{ km}$  in diameter. Deeper, less impact-processed material may contain more volatile ice species that

could provide a source of surface activity around recent impact sites. Such activity may range from small, geyser-like plumes activated by impactors just large enough to penetrate a processed regolith, up to the production of full-scale comae generated by the largest impactors (see Fitzsimmons and Fletcher [1999] in this regard).

## b. Mass Loss Due to Ejecta Escape

The same impacts responsible for overturning and reworking the surface of an EKO and covering its surface with craters will also erode and remove a fraction of that surface through the escape of ejecta launched at speeds greater than the escape speed of the target.

Standard impact scaling laws indicate that for strong targets with radii less than  $\sim 75$ – $150$  m, ejecta speeds should exceed the escape speed of the object. In a purely strength-scaling cratering regime, the volume eroded from the target is directly proportional to the volume of the impactor:  $V_{erode}(D) = hD^3$ , where  $D$  is the projectile diameter, and  $h \approx 120$  as suggested by Holsapple (1993). For larger targets, such as a 100 km-scale radius EKO, larger craters are excavated in the gravity-scaling regime and a much smaller fraction of the ejecta is launched at greater than the escape speed. Even for targets as small as 1 km radius comets, a significant fraction of impact ejecta may be retained (Ryan and Melosh 1998). For a 100 km-scale radius icy EKO, and the mechanical properties described just below Eqn. (3), the transition crater diameter between the strength-scaling and gravity-scaling regimes is of order 40–50 m, about the size of craters produced by the smallest objects considered in our model ( $r=4$  m). As in the strength-scaling regime, the volume eroded per volume of projectile for gravity-scaling cratering is independent of the size of the impactor,  $V_{erode}(D) = h'D^3$ , but here  $h'$  is much smaller than  $h$ , of order 3–4 for a 100 km-scale radius icy object in the EKB (see the Appendix of Geissler *et al.* (1996) for a more complete discussion of mass loss from small objects due to impact ejecta erosion).

With the above mass loss assumptions and the EKO population and collision time scales calculated from our model, we can estimate the magnitude of the surface loss from comets and large EKOs due to escape of impact ejecta. Time-averaged mass loss rates from a 100 km radius EKO due to impacts with  $r > 4$  m projectiles range from  $\sim 4 \times 10^8$  to  $7 \times 10^9$  g  $\text{yr}^{-1}$  for  $R$  between 35 and 45 AU and  $\langle e \rangle$  between 0.0256 and 0.2048. Over 3.5 Gyr, this amounts to some 10–100 m of surface loss. Mass loss rates from 1 km radius comets range from  $6 \times 10^5$  to  $2 \times 10^6$  g  $\text{yr}^{-1}$  under the end-member assumption of cratering in the strength regime, amounting to  $\sim 110$ – $390$  m of surface loss over 3.5 Gyr. Gravity-regime cratering would result in lower mass loss rates and less surface erosion due to the larger fraction of retained ejecta. We suspect that most of the surface loss effects due to impacts will be localized primarily around larger impact sites, and the impact-undisturbed surface fraction (perhaps 90% for a minimum impact radius of 4 m) will be considerably less damaged. In contrast, recall that fully a third of the entire surface of a typical large EKO may have been processed over the past 3.5 Gyr by mechanical overturning and regolith formation.

## 6. COLLISION RATES ON PLUTO AND CHARON RE-EVALUATED

Weissman and Stern (1994) estimated impact rates of EKB and Oort Cloud comets onto both Pluto and Charon given early estimates of EKB population numbers. They showed that the outer Oort Cloud is a negligible source of impactors and that the dominant sources of impactors on both bodies are EKB and inner Oort Cloud comets, with the EKB population dominating over the inner OC by factors of a few, contributing a flux of some 2400 impacts over the age of the solar system onto Pluto’s surface, and 460 impacts onto Charon’s surface. Here we re-examine the EKB flux onto Pluto and Charon using newer EKB population estimates described above in §3.

Figure 6 shows the number of EKO impacts onto Pluto and Charon over 3.5 Gyr, as a function of impactor radius. As above, the calculated flux of impactors includes impact cross-section enhancement due to the focusing effects of Pluto’s and Charon’s gravitational fields. Over 3.5 Gyr, the total number of  $r = 1$  km comets striking Pluto and Charon is approximately  $8.9 \times 10^3$  and  $1.1 \times 10^3$ , respectively. (To compare with the Weissman and Stern (1994) results, this amounts to some  $1 \times 10^4$  and  $1.2 \times 10^3$  impacts onto Pluto and Charon, respectively, over 4.5 Gyr). Clearly, improved EKB population parameters have increased the Weissman and Stern (1994) fluxes by  $\sim 3$ – $5$  times. Impacts of 1 km radius comets onto Pluto occur on time scales of  $\sim 3.9 \times 10^5$  yr. Similar impacts on Charon occur on  $\sim 3.2 \times 10^6$  yr time scales. The largest EKOs expected to have impacted Pluto and Charon during the last 3.5 Gyr have radii of  $r = 40$  and 20 km, respectively. We find from Eq. 3 that the resulting largest crater diameters on both bodies due to present-day EKB collisions are roughly 123 and 75 km, respectively. Larger impact basins resulting from earlier, massive impacts may well underly these more recent craters.

If we simply sum up the total area covered by craters on Pluto’s surface over 3.5 Gyr, we find cumulative cratered surface fractions of  $\sim 40\%$ ,  $0.4\%$ , and  $0.003\%$  for  $r > 4$ , 40, and 400 m projectiles, respectively. However, the hydrodynamic escape of Pluto’s atmosphere (Trafton *et al.* 1997) implies that there has been  $\sim 1$ – $5$  km of surface loss due to sublimation, if the present escape flux has been maintained over the age of the solar system. For craters and basins with depths of 1 km ( $\sim 5$  km diameter), Pluto’s surface may therefore be comparatively young, of order  $2 \times 10^8$  yr. On such a time scale, the cumulative cratered fraction drops to  $\sim 2\%$ ,  $0.02\%$ , and  $2 \times 10^{-4}\%$  for  $r > 4$ , 40, and 400 m projectiles, respectively.

Unlike Pluto, Charon’s surface is not losing significant volatiles to atmospheric escape (Trafton *et al.* 1997), and so should record the cumulative flux of projectiles encountered over its lifetime. Over 3.5 Gyr, the cumulative cratered fractions for Charon are  $\sim 20\%$ ,  $0.2\%$ , and  $0.002\%$  for  $r > 4$ , 40, and 400 m projectiles, respectively.

When the highly-anticipated Pluto-Kuiper Express reconnaissance mission reaches the Pluto-Charon system, one should quite clearly expect Charon to display an older surface reflecting the time-integrated flux of projectiles. At the same time, Pluto’s surface should

reflect the recent production population, thereby showing the essentially-instantaneous (i.e., recent-times) impact flux.

Given the modeled EKB flux through the Pluto-Charon system, we can also calculate the size of the smallest surviving primordial satellite in the system. The Pluto-Charon pair likely formed as the result of a giant impact which may have left smaller satellites or debris orbiting Pluto after the accretion of Charon. We calculate that at 39 AU, with  $\langle e \rangle = 0.2048$ , objects smaller than  $r \approx 1.5\text{--}2$  km have catastrophic disruption lifetimes less than 3.5 Gyr. Any primordial Pluto satellites smaller than this should have been destroyed by collisions with EKB projectiles. Analysis of archival HST images by Stern *et al.* (1994) shows that at the 90% confidence level, no Pluto satellites larger than  $r \approx 140$ , 46, and 42 km exist inside the Charon instability strip, between 1 and 2 arcsec from Pluto (i.e., between 1.1 and 2.2 Charon’s orbital radius), and outside 2 arcsec from Pluto, respectively. If the Pluto-Charon system harbors undiscovered, surviving primordial satellites, we conclude that they will most likely be in the  $r \approx 2\text{--}46$  km size range.

## 7. COLLISION RATES IN THE CENTAUR REGION

We have also applied our model to examine collision rates in the Centaur region, between 5 and 30 AU. Slow leakage of objects from the EKB due to planetary perturbations sustains a population of objects in the giant planet region with dynamical lifetimes of order  $5 \times 10^7$  yr (Duncan *et al.* 1995; Levison & Duncan 1997). Chiron, Pholus, and the other presently known Centaurs in this region are thus recognized as emissaries from the EKB, delivered to a less distant region of the solar system, enabling more detailed observational studies of Centaurs than of EKO’s. We therefore wish to understand how EKB collisional histories recorded on the surfaces of Centaurs have been modified in the Centaur region.

Figure 7 shows a collisional erosion/accretion boundary plot similar to Fig. 1, but for the population of known Centaurs. The higher average orbital speeds and eccentricities of the Centaurs conspire together to place them strongly in the erosive regime, so that growth of larger objects by accretion is not possible in that region at the present time. Such erosive collisions will both contribute ejecta and fine dust in the 5–30 AU zone, and cause EKO’s in that region to slowly, but surely, lose mass while in transit through this region.

To quantify such effects, we constructed a model disk of Centaur objects based upon observational constraints on the population by Jedicke and Herron (1997). Their determination of the detection efficiency of the Spacewatch survey system, combined with the observed absolute magnitude distribution of observed Centaurs and a model of the orbit distribution based on numerical integrations of Levison and Duncan (1997), allowed Jedicke and Herron to determine that in the 5–30 AU region there must be fewer than  $\sim 2000$  objects in the absolute magnitude range  $-4 < H < 10.5$  ( $r > 26$  km for  $p_\nu = 0.04$ ). Assuming that the Centaur absolute magnitude distribution can be represented by a power law, they find a slope parameter  $b = 4.05$  over the relevant size range. This slope is just slightly less steep than that

favored for EKO by Weissman and Levison (1997) over the same size range. As the Centaurs are a dynamical sampling of the EKB population, we therefore continue to use the WL97 population size distribution as our favored size distribution, but we will also report Centaur collision rates assuming the Jedicke and Herron best-fit power law. Finally, we distribute the estimated total number of Centaurs throughout a disk ranging from 5–30 AU with a helio-centric surface mass density dependence of  $R^{1.3}$  (Levison and Duncan 1997), and calculate collision rates as above.

Figure 8 shows the resulting number of impacts onto a Chiron-size object ( $r \approx 90$  km) at 14 AU, over a typical  $5 \times 10^7$  yr dynamical lifetime, as a function of impactor size. Collision time scales at 14 AU are  $\sim 300$  times longer than for a comparable body at 40 AU. At 14 AU, cratering collisions of 1 km radius comets onto Chiron-size targets occur every  $\sim 60$  Gyr (every  $\sim 4$  Gyr assuming the Jedicke and Herron best-fit size distribution extends to  $r = 1$  km). Clearly, there is very little collisional evolution in Centaur region. We therefore conclude that the cumulative collisional and cratering history of Centaurs is dominated by the time they spent in Kuiper Belt, and that only a negligible amount of collisional processing occurs while they are extant in the Centaur region.

Hughes (1991) has proposed that surface activity responsible for outbursts and coma around Chiron might be the result of cratering impacts exposing supervolatile ices. Analysis of pre-discovery images of Chiron (Bus *et al.* 1999) indicates variability in surface activity on time scales of a few to several years. Our model calculations for Chiron yield cratering time scales with 4 m radius projectiles of  $\sim 1$  Myr for a WL97 size distribution. Even assuming that the Jedicke and Herron power law size distribution is valid to sizes as small as 4 m, the mean time between impacts will be of order 200 yr, significantly longer than the observed time scale of outburst activity on Chiron. We might be fortunate to witness one such cratering impact on a single object, but given the lengthy time scales, one must conclude that the predominant surface activity on Chiron is not caused by impacts.

## 8. CONCLUSIONS AND DISCUSSION

We have updated our previous collision rate model (Stern 1995) to include a more precise treatment of encounter speeds and collision cross sections, and have incorporated new estimates of the EKB population size and structure (WL97). Based on this we find:

1. Collision time scales in the present EKB for 1 km radius comets onto 100 km radius objects are  $\sim 6.5 \times 10^7$ – $4.1 \times 10^8$  yr. Over 3.5 Gyr this amounts to  $\sim 8$ – $54$  such impacts onto a single 100 km target. Given the estimated population of such objects in the present EKB, there should be one such impact somewhere in the 30–50 AU region every  $\sim 1.4$ – $9.0 \times 10^4$  yr. Impacts of 4 m radius projectiles onto 1 km radius comets occur on  $2.5$ – $4.7 \times 10^7$  yr time scales, resulting in  $\sim 90$ – $300$  cratering impacts with  $r > 4$  m projectiles onto individual comets. Over the entire population of  $\sim 2 \times 10^9$  comets in the EKB, there should be one such collision every few days.

2. Assuming relative encounter speeds of  $\sim 1.1\text{--}1.4\text{ km s}^{-1}$  between objects in the 30–50 AU region, and using impact strengths from published scaling laws, we estimate that 100 km-scale radius EKO can be catastrophically disrupted by 53–84 km radius projectiles, yielding disruption lifetimes of  $3\text{--}8 \times 10^{12}$  yr in the present EKB. Catastrophic disruption time scales for 1 km radius comets range from 1–10 Gyr.

3. Objects smaller than about  $r = 2.5$  km have collisional disruption lifetimes less than 3.5 Gyr in the present-day EKB collisional environment. It can be expected that most small, comet-size bodies, even primordial objects not formed as collision fragments, have been heavily damaged in their interiors by large collisions.

4. The cumulative fraction of the surface area of 1 and 100 km radius objects cratered by projectiles with  $r > 4$  m ranges from a few to a few tens percent over 3.5 Gyr.

5. Over 3.5 Gyr, Pluto and Charon are estimated to have been impacted by  $8.9 \times 10^3$  and  $1.1 \times 10^3$  1 km radius comets, respectively. Impacts of 1 km radius comets onto Pluto occur on time scales of  $\sim 3.9 \times 10^5$  yr. Similar impacts on Charon occur on  $\sim 3.2 \times 10^6$  yr time scales. Because of the hydrodynamic escape of Pluto’s atmosphere, its surface may be comparatively young for craters with depths less than about 1 km. In this case, fresh craters may cover less than 2% of Pluto’s surface due to impacts by projectiles with radii greater than 4 m. Charon’s surface, in contrast, should appear substantially older, recording a history of impacts since its formation, and having more than 20% of its surface cratered by projectiles with radii greater than 4 m.

6. In the Centaur region, collisions of 1 km radius comets onto 100 km radius targets (roughly Chiron’s size) occur on time scales as long as  $\sim 60$  Gyr. Collision time scales at 14 AU are  $\sim 300$  times longer than those for comparable bodies at 40 AU. The collisional and cratering histories of Centaurs are dominated by the time they spent in the EKB. The predominant surface activity on Chiron is not likely caused by impacts.

Our results, like those of Davis and Farinella (1997) and Stern (1995), show that the small bodies we call comets coming from the EKB must be young compared to the age of the Solar System. This will not be the case in the Oort Cloud, where Stern (1988) showed collisions are rare. Thus, we can predict a major difference between OC and EKB comets: age, which should manifest itself in CRE age, crater counts, regolith reworking, radiation effects on surface microstructure, and perhaps even albedo and upper crust chemistry.

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## Figure Captions

**Figure 1.** The critical eccentricity ( $e^*$ ) boundary between erosional and accretional outcomes for collisions between Edgeworth-Kuiper Belt objects. Critical eccentricity boundaries are shown for both strong ( $\rho = 2 \text{ g cm}^{-3}$  and  $S_o = 3 \times 10^6 \text{ erg g}^{-1}$ ) and weak ( $\rho = 0.5 \text{ g cm}^{-3}$  and  $S_o = 3 \times 10^4 \text{ erg g}^{-1}$ ) targets at two representative heliocentric distances (30 and 50 AU). The collision strengths chosen for the strong and weak cases bound a wide range of material properties and, we believe, the likely range of collision strength parameters of Kuiper Belt Objects.

**Figure 2.** The total number of impacts onto 102 km and 1 km radius EKO over 3.5 Gyr, as a function of projectile radius. The bend in the plotted curves at impactor radii of 10 km is a reflection of the shape of the EKO size distribution adopted in our study (Weissman and Levison 1997).

**Figure 3.** Collisional disruption lifetime for EKOs as a function of target size, calculated at 35 and 45 AU with  $\langle e \rangle = 0.2048$ . Critical specific energies for catastrophic disruption,  $Q_D^*$ , were assumed to be in the mid-range of those from the published scaling laws referred to in the text.

**Figure 4.** Fraction of the surface area of 102 km and 1 km radius EKOs cratered during 3.5 Gyr, as a function of projectile radius.

**Figure 5.** Kinetic energy partitioned into impact vaporization of the surfaces of 102 km and 1 km EKOs during 3.5 Gyr, as a function of impactor radius.

**Figure 6.** Total number of impacts onto Pluto and Charon over 3.5 Gyr, as a function of impactor size.

**Figure 7.** Same as Fig. 1, except for the population of Centaur objects.

**Figure 8.** Total number of impacts onto a roughly Chiron-size Centaur of a typical dynamical lifetime in the giant planet region of 50 Myr, as a function of impactor size.



















